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Life Cycle Assessment of Fuel Ethanol from Cassava in Thailand*

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Abstract

Goal and Scope. A well-to-wheel analysis has been conducted for cassava-based ethanol (CE) in Thailand. The aim of the analysis is to assess the potentials of CE in the form of gasohol E10 for promoting energy security and reducing environmental impacts in comparison with conventional gasoline (CG).

Method. In the LCA procedure, three separate but interrelated components: inventory analysis, characterization and interpretation were performed for the complete chain of the fuel life cycle. To compare gasohol E10 and CG, this study addressed their impact potentials per gasoline-equivalent litre, taking into account the performance difference between gasohol and gasoline in an explosion motor.

Results and Discussions. The results obtained show that CE in the form of E10, along its whole life cycle, reduces certain environmental loads compared to CG. The percentage reductions relative to CG are 6.1% for fossil energy use, 6.0% for global warming potential, 6.8% for acidification, and 12.2% for nutrient enrichment. Using biomass in place of fossil fuels for process energy in the manufacture of ethanol leads to improved overall life cycle energy and environmental performance of ethanol blends relative to CG.

Conclusions and Outlook. The LCA brings to light the key areas in the ethanol production cycle that researchers and technicians need to work on to maximize ethanol's contribution to energy security and environmental sustainability

Keywords: Cassava ethanol (CE); energy; environmental performance; life cycle assessment (LCA); Thailand

Introduction

The 1970s marked a new age of uncertainty when the shortage of world oil supplies and volatile oil prices put many countries in severe energy insecurity and economic hardships. Among various candidate alternative fuels that emerged, biomass-derived ethanol actually had a chance to dominate the fuel market before the introduction of cheap and abundant supplies of petroleum. Not until the early 1980s, when the Brazilian government launched the Proalcool programme, was interest in ethanol renewed. Since then, ethanol overall output has increased rapidly and this trend goes along with an ever wider geographical spread all over the world, originating from those countries located in the western hemisphere, Brazil, the US, Canada, etc.

Since the re-emergence of ethanol, researchers have evaluated the fuel as a potential gasoline substitute using a generally applicable assessment tool namely, life cycle assessment (LCA). The two key parameters that most of the ethanol case studies address are energy and environmental performance [1-4]. Not only providing a complete picture of ethanol production and use, LCA also helps identify specific areas where technological innovation or strategic policy is needed to make such an energy alternative practical and feasible.

The fastest emerging market for fuel ethanol in Asia, Thailand hopes a shift of its surplus farm products to ethanol could, in the short term, reduce the country's oil import bills. What can be expected more from ethanol is its contribution to long-term energy security and environmental sustainability. In Thailand, both sugar and starch crops are considered potential feedstock materials for commercial ethanol production. At present, ethanol in the form of gasohol available at the Thai gas stations is derived mainly from molasses, a by-product of the sugar industry. However, the main disadvantage of molasses-based ethanol lies in supply versus demand, which has induced a shift towards cassava-based ethanol (CE). To demonstrate the feasibility of feedstock conversion to ethanol on a commercial scale, a research team at the Cassava and Starch Technology Research Unit, Bangkok, Thailand has conducted research on pilot-scale production of ethanol from cassava [5]. The flow chart representing the production process for a CE case study in Thailand is shown in **Fig. 1**.

So far, it is unclear whether ethanol could work in Thailand as it does in other countries. A satisfying conclusion cannot be reached unless an integrated assessment of ethanol production and use in the country is conducted. The objective of this study is to perform a life cycle analysis of energy and environmental impacts of using cassava-based gasohol as a conventional gasoline (CG) substitute in Thailand. The following parameters have been considered in the analysis.

- Energy use (MJ energy carrier), specified as: 1) total gross energy use (all energy inputs, including both fossil and non fossil-based energy); 2) Net energy use (total energy use, excluding energy recovered from system co-products); 3) Fossil energy use; and 4) Petroleum use
- Environmental impact potentials in four categories: 1) Global Warming Potential (GWP); 2) Acidification; 3) Nutrient enrichment; and 4) Photochemical Ozone Creation Potential (POCP)

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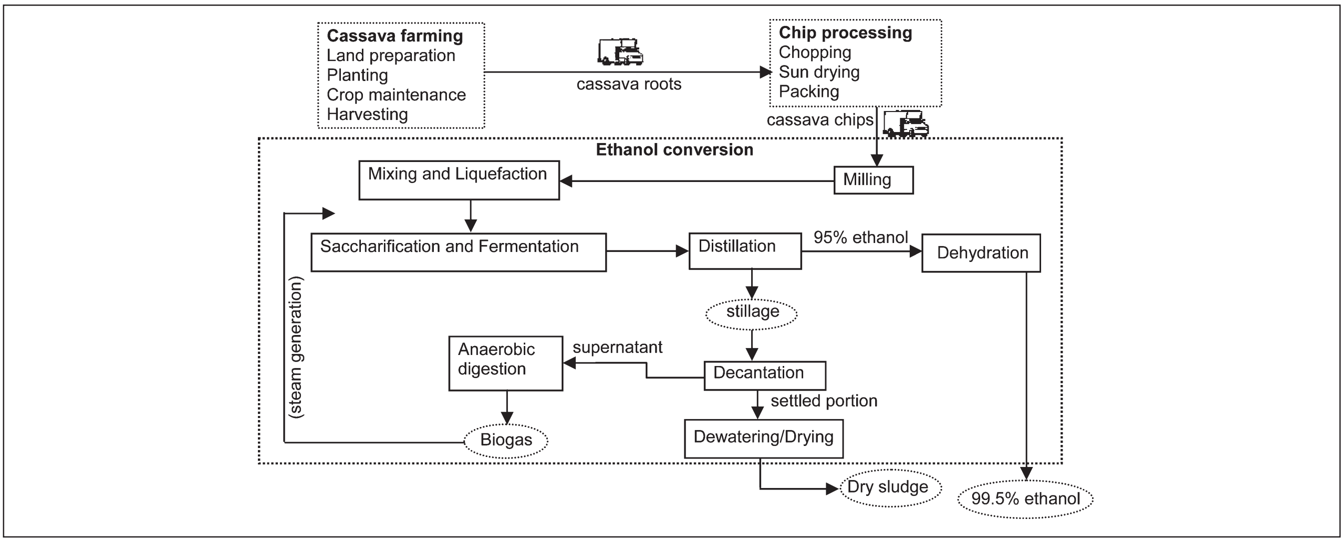

Fig. 1: Flow chart of cassava based ethanol production process in Thailand

- Land use: According to the previous government target, of the total 20 million tonnes of the annual national cassava output, the surplus 20% would be used to produce 2 million litres (ML) of CE a day [6]. In this case, there is no change in land use. As the new CE target set up by the government has resulted in an additional demand of 1.4 ML a day [7], the strategic plan for cassava has to change. This essentially bids away part of the commodity from its current use in chip/pellet industries, since there is no scheme to expand planted area for the crop even under biofuel promotion policy. How much land would be used for CE has been addressed using simple estimates based on CE yield per hectare of land [8].

1 Life Cycle Assessment

1.1 Ethanol fuel case study and functional unit

The Thai government plans to construct 12 CE plants nationwide within 2009. Of the total CE output of 3.4 ML a day, 1.6 ML would be contributed by 3 CE plants located in the Eastern Region of the country (ERTh) [7]. Accounting for the second largest share of the total national cassava production [9], the ERTh is most suitable for CE production as far as supply potential is concerned. In Thailand, the E10 blend is the first stage of the government ethanol policy to be followed by higher blends, e.g. E20, E85 in the near future [10]. Blending ethanol to make E10 is carried out in oil refineries. Most oil refineries in the country are located in the ERTh leading to fuel savings in transportation of ethanol to oil refineries. Good transportation infrastructure and public utilities here are other important factors enhancing the approval of a cluster of CE factories most expected to serve both domestic demand and export markets.

In this study, the functional unit (FU) chosen to compare the life cycle energy and environmental performance of gasohol E10 and CG is one litre gasoline equivalent consumed by a new passenger car to travel a specific distance. According to the tests conducted by PTT [11], a new passenger car (Toyota 1.6 L/2000) runs around 13.46 km per litre of CG, whereas it runs 13.31 km per litre of E10. The comparison in vehicle fuel economy reveals that 1 L of E10 is equal to 0.989 L of CG.

1.2 Co-product allocation and scenarios

A valuable co-product of ethanol production, stillage can be used in either one of two ways. Commercial corn-ethanol plants in the US and Canada commonly market stillage as distillers dried grain with solubles [1-4]. Alternatively, the slop supernatant separated from stillage can be utilized for energy generation via the biogas pathway, whereas the settled portion is recommended to be salvaged for replacement of fertilizer nutrients (see Fig. 1). Biogas utilization is currently applied in ethanol factories in Thailand. After being separated from the supernatant, the settled portion still has a very high moisture content of about 86% [5] which creates difficulties in nutrient recovery. The energy used in transporting this bulky material from ethanol plants back to cassava farms would offset the energy credits in replacement of fertilizer nutrients; this is the same problem as with the use of livestock manure/organic residues [12,13]. Applying heat to lower the moisture content of this bio-fertilizer to facilitate handling and transporting is also energy intensive. More research is required to assess the feasibility of such a waste utilization scheme, especially when the 12 approved CE plants start operation in Thailand. In the short term, this type of material is expected to be suitably collected and stored prior to land spreading in the vicinity of ethanol plants. Lacking information on the use of the settled portion separated from stillage, this study considered only biogas as co-product of the CE production cycle.

It is obvious that sources of energy input in the ethanol conversion process are critical for determining whether the fuel is more environmentally friendly than CG. The process energy can be derived either from fossil fuels or from waste biomass. In Thailand, there is an incentive to use biomass fuels in place of fossil fuels for industrial processes. Accord-

Table 1: Scenarios of cassava fuel ethanol study

Case	Process Energy Source
Scenario 1: E10-a, E85-a	Fuel oil only
Scenario 2 (base case): E10-b, E85-b	Biogas and fuel oil
Scenario 3: E10-c, E85-c	Biogas and rice husk

ingly, three scenarios concerned with process energy sources in the ethanol conversion stage have been examined (**Table 1**). The first scenario is based on the assumption that the energy used to drive the ethanol conversion process is simply derived from fossil sources. The second reflects the existing situation of ethanol factories in Thailand; process energy source comprises both biomass and fossil fuels. The third one assumes that the plant's energy demand can be met totally by using its co-product (biogas), and biomass, e.g. rice husk, as an external energy source. Among various biomass energy resources relevant to Thailand, bagasse and rice husk are ranked first and second as per supply outputs [14], but bagasse is already being utilized by the sugar industry. To figure out how a high content of ethanol in blends would affect the results, the same calculation procedure quantifying energy use and emissions was applied to E85.

1.3 System boundary and data sources

As shown in **Fig. 2**, four main unit processes of the cassava-based E10/E85 fuel system for the life cycle inventory (LCI) are cassava production, ethanol conversion, transportation and fuel combustion in vehicles. The system boundary also includes various sub-processes associated with the four main processes, viz. agrochemical manufacturing, crude oil extraction/refining, electricity production and solar energy capturing. The preparation of organic fertilizer used in cassava farming, performed by simply mixing manure with rice husk, was excluded from the system boundary. Also energy costs and environmental loads from the manufacturing of chemicals used in ethanol conversion were considered negligible compared to other inputs and thus not included in the analysis. Solar energy captured by cassava crops and later transformed to the heating value of ethanol was counted as the non-fossil energy consumed when ethanol is burned in vehicles (i.e. use stage).

An unresolved issue related to feedstock cultivation in CE production cycle is accounting for human labour input. It has been a matter of controversy whether human labour should be excluded or included and, in case of inclusion, methods for quantification have varied greatly. Fluck [15] summarized 9 methods and split them into two groups. Methods in the first group are recommended to be used for subsistence agricultural systems; they do not count any energy flows that may be sequestered in human labour. The second-group methods can be applied to any levels of agricultural technology where consumption of fossil fuels is prevalent; they are most likely compatible with a life cycle energy analysis tracing back to primary energy use. Due to data availability, this study employed the 'Life-Style Support Energy' (LSSE) method recommended by Odum [16] to derive energy value of agricultural labour in Thailand. Detailed derivation of the value can be found in Nguyen et al. [8]. Further estimates of fossil energy and petroleum consumption to support labour were done, using information on Thailand's primary energy use by fuel sources [17]. Consistent with an evaluation of human labour energy based on the 'LSSE' method, further assessments of environmental loads need to take into account emissions associated with primary energy consumed to support labour work. These category emissions were estimated by multiplying the primary energy consumed to support labour by the ratio of total national emission of air pollutants [18-20] to total national primary energy use [21].

In the context of lacking a generally acceptable accounting method, any attempt to quantify human labour in an agricultural system should be explained and interpreted with great care [12]. Thus, this study displays the LCA results

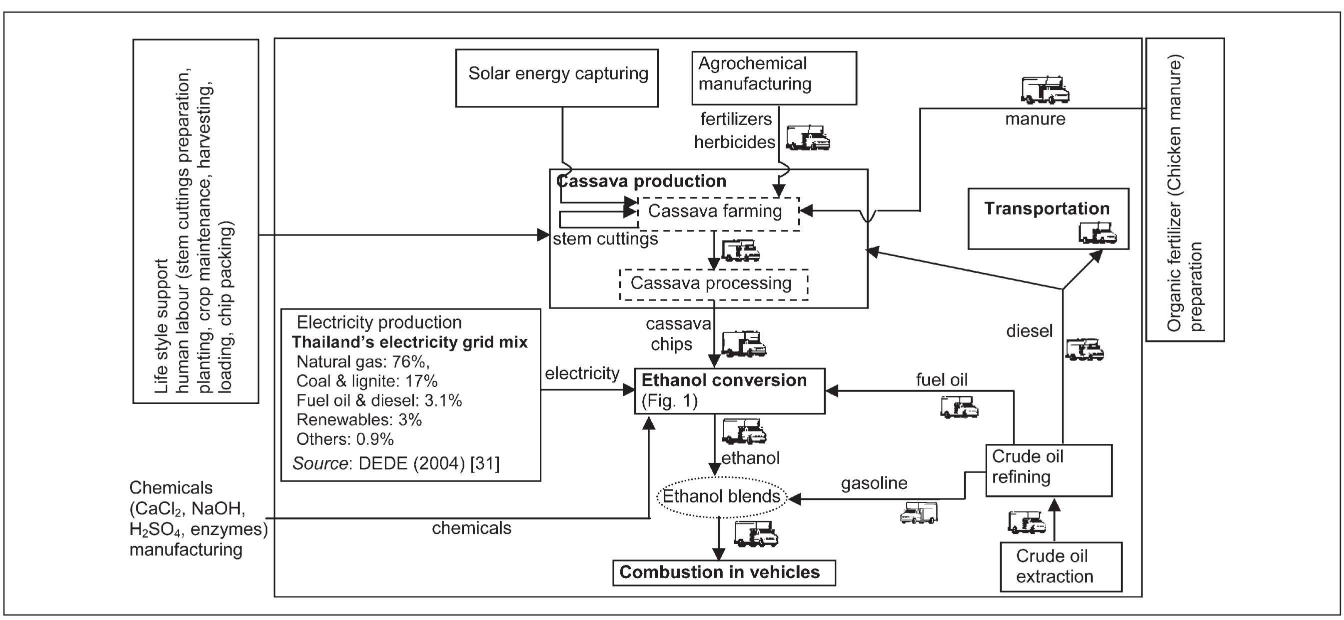

Fig. 2: System boundary of the cassava-based E10/E85 fuel life cycle (base case)

Table 2: The procedure for life cycle inventory of cassava-based E10/E85 fuel

Main unit process	Data required	Data sources	Collecting method	Data processing
Cassava production	Fuel use Fertilizer use Herbicide use Labour use	Cassava farmers Thai research reports [23–26] Manager of cassava processing plant [27]	Questionnaire/ On-site interview Literature review	**Energy use:** – Diesel, fuel oil: TEI [29], IFAS/FU [30] – Fertilizer, herbicide: Helsel [13], GREET [22] – Labour: Nguyen et al. [8], IEA [17] – Electricity: DEDE [31] – Rice husk (scenario 3): Chungsangunsit et al. [32] **Emissions:** – Diesel, fuel oil (direct emissions, i.e. emissions from fuel combustion, and indirect emissions, i.e. emissions from fuel manufacturing): GREET [22] – Fertilizer, herbicide manufacturing: GREET [22] – Fertilizer application (N_2O emission): IPCC [33], IPCC [34] – Human labour: ONEP [18], World Bank/DEDP [19], EarthTrends [20], DEDE [21] – Electricity: Lohsomboon and Jirajariyavech [35] – Biomass/biogas combustion in boilers: DMU/NERI [36]
Ethanol conversion	Fuel oil use Electricity use Biogas recovery/use	Thai research report [5]	Literature review	
Transportation related to cassava production Transportation related to ethanol conversion	Distance Transport mode/capacity	Cassava farmers Bulk terminal company [28] Assumptions (see **Table 3**)	Questionnaire/ Interview	
Crude oil recovery Gasoline refining	Fuel energy content	Thai research report [29]	Literature review	**Energy use:** TEI [29], IFAS/FU [30], GREET [22] **Emissions**: GREET [22]
Fuel combustion (Use stage) – CG, E10, E85	Fuel energy content Fuel economy	Thai research report [29] USDA research report [3] CG and E10: PTT [11] E85: flexible fueled vehicles (FFV) not available in Thailand at present	Literature review	**Energy use:** – Gasoline: TEI [29] – E10, E85 Gasoline portion: TEI [29], ethanol portion: using heating value of ethanol [3] (non-fossil energy) **Emissions:** – Major emissions from cars running on CG, E10: PTT [11] – Emissions from FFV running on E85: estimated from [22]

without accounting for human labour, which is put outside the system boundary (see Fig. 2). The results including labour are given in a separate section as a sensitivity analysis.

The procedure for making an LCI of cassava-based E10/E85 fuel is summarized in **Table 2**. The fuel life cycle environmental impacts are contributed by upstream (feedstock production, fuel conversion) stages and a use stage (fuel combustion). With ethanol blends, *feedstock stage* comprises cassava production and crude oil recovery and *fuel stage* is a combination of ethanol conversion and CG refining. As seen, data for the study were collected in different ways from different sources. An important step of the LCI procedure is processing primary data to quantify energy use and emissions associated with each unit process, using well-known models, conceptual guidelines and databases (see Table 2). Note that in the GHG emission estimate, only fossil CO_2 emissions were considered; biomass-based CO_2 emissions were treated as net zero.

2 Results and Discussions

2.1 Life cycle energy and environmental impact performance

Table 4 summarizes the LCA characterization results for E10-b, E85-b and CG. Change represents impacts of substituting either of the two alternatives for CG. Negative change implies a reduction in environmental loads compared to CG, whereas positive change denotes an increase. Breakdown of

Table 3: Assumptions about transportation activities related to ethanol conversion phase

Type of materials, products	Transport mode	Capacity (tonnes)	Average distance (km)
Cassava chips from cassava processing plants to CE plants	Diesel truck	15–20	100
Ethanol from factories to oil refineries	Diesel truck	10–12	150
Gasohol from oil refineries to gas stations	Diesel truck	10–12	180

Table 4: LCA characterization results for 9 impact categories (displayed per functional unit)

Impact category	CG	E10-b		E85-b	
			% change		% change
Total gross energy use (MJ)	38.70	38.78	+0.2	34.02	–12.1
Net energy use (MJ)	38.70	38.48	–0.6	31.57	–18.4
Fossil energy use (MJ)	38.59	36.22	–6.1	14.32	–62.9
Petroleum use (MJ)	34.83	32.65	–6.3	12.58	–63.9
GWP (kg CO_2 eq.)	3.00	2.81	–6.0	1.15	–61.6
Acidification (g SO_2 eq.)	3.00	3.07	–6.8	4.90	+48.4
Nutrient enrichment (g NO_3^- eq.)	5.00	4.38	–12.2	6.67	+33.8
POCP (g C_2H_4 eq.)	1.53	1.54	+0.6	1.27	–17.1
Land use (m^2 in one year)	–	0.27		2.19	

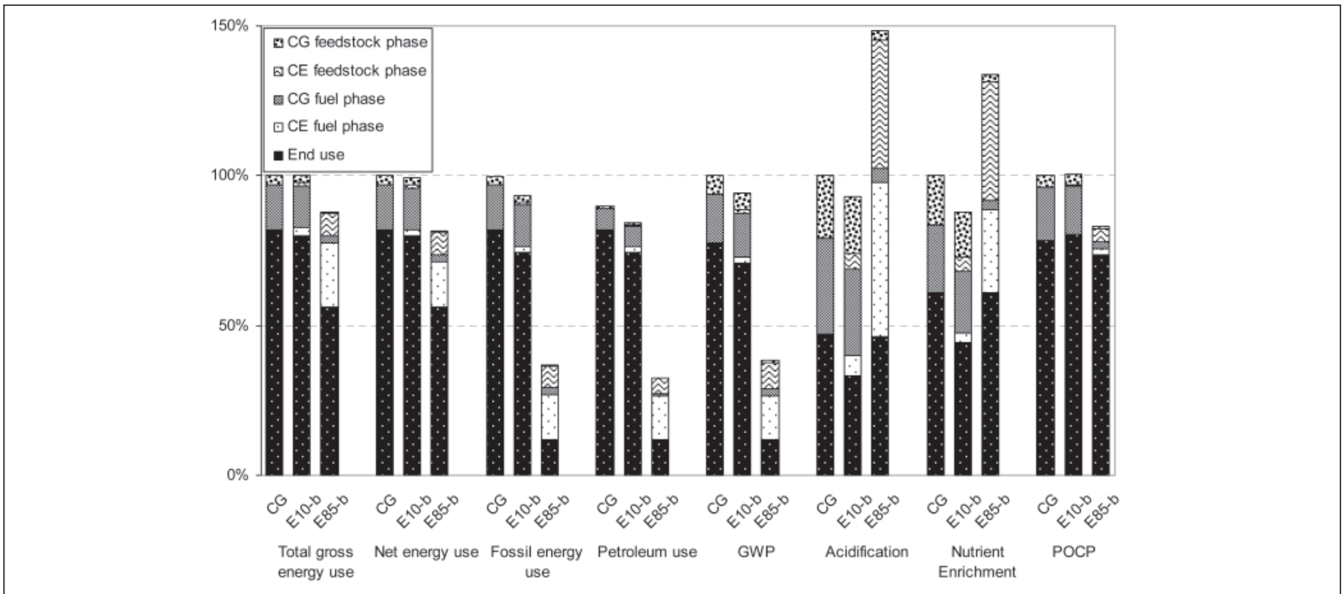

Fig. 3: Contributions of stages (feedstock, fuel, end use) to life cycle energy environmental performance of CG, E10-b and E85-b

contributions from the three stages (feedstock, fuel and end use) to the life cycle energy and environmental performance of CG, E10-b and E85-b is shown in **Fig. 3**.

Table 4 shows clear advantages of using CE in the form of either E85 or E10 as a transportation fuel over CG in terms of reductions in fossil energy use, petroleum use and GWP. The reductions mainly result from the absence of fossil-based liquid fuel and consequently fossil-based CO_2 emissions from the combustion of ethanol portion in the blends. It is reasonable that the magnitude of the reductions is proportional to the percentage of ethanol mixed with CG. Using E85 is even more advantageous than E10 considering '% change' in total gross energy use and net energy use relative to gasoline.

Regarding other environmental impact potentials, e.g. acidification, nutrient enrichment and POCP, the results come out in opposite direction for E10 and E85. Along its whole life cycle, E10 produces positive impacts over CG on acidification and nutrient enrichment, but negligible impact on POCP. In contrast, the production and use of E85 leads to more severe impacts on acidification and nutrient enrichment but less damaging impact on POCP than CG. As illustrated in Fig. 3, in terms of acidification and nutrient enrichment, lower impacts from the use stage of E10 favour the overall life cycle impacts of the fuel mixture over CG. As ethanol content in gasoline reaches 85%, the net changes in the two impact categories relative to CG are dominated by higher impacts from the upstream of the ethanol fuel life cycle. For POCP, a slightly higher impact from the use stage of E10 over that of CG is nearly compensated by lower impact from the upstream. Improvement appears with E85 where a combination of lower impacts from the fuel stage and use stage completely offset the slightly higher impact from the feedstock stage.

Fig. 3 also reveals that a high percentage of energy use and environmental impact potentials is contributed by the combustion of the fuel mixture and the production of the major fuel component, i.e. CG if the mixture is E10 or ethanol if the mixture is E85. Obviously, the environmental impacts from ethanol production cycle play a more dominant role in a high-level ethanol-gasoline blend than in a low-level one.

Presented in Table 4 is a rough evaluation of the area of agricultural land used for growing feedstock to produce the ethanol portion in the two ethanol blends. To meet the government target of 3.4 ML of CE a day, approximately 0.335 million hectares (Mha) a year is required. This accounts for 32% of the total national cassava harvested area in 2004 (1.057 Mha) [9]. However, only 0.138 Mha (13% of 1.057 Mha) is to be considered for a possible change in the end use of the crop harvested, as mentioned before. This is essentially a shift of the use of some of the cassava chips from animal feed to ethanol which implies that the substituted animal feed must be provided from other sources. The impact of this change needs to be studied further in terms of its effect on land use.

2.2 Breakdown of results – Comparison between scenarios

For a better understanding of the results obtained, further breakdown of contributions to the environmental impacts from the base case ethanol production cycle is performed (see Fig. 4).

Fig. 4 indicates that ethanol conversion is the main source of most impact categories, e.g. energy use, GWP, acidification and nutrient enrichment. The relatively high contribution made by this unit process is due to the use of fuel oil as the main process energy source. Cassava production is also notable for its contribution to acidification, nutrient enrichment and POCP. Acidification originates principally from SO_2 emission from the manufacturing of P fertilizer and NO_x emission (direct and indirect) from diesel used to power farm tractors. This amount of NO_x also contributes to nutrient enrichment. However, the largest contributor to nutrient enrichment from cassava production is N_2O soil emissions from N fertilizer application, as seen in Fig. 4. Its percentage contribution is second after only 'fuel oil use' in ethanol conversion. Regarding POCP, the relatively high contribution by feedstock production compared to fuel conversion and transportation is due to CO and VOC emissions from the use of diesel fuel to run farm tractors (di-

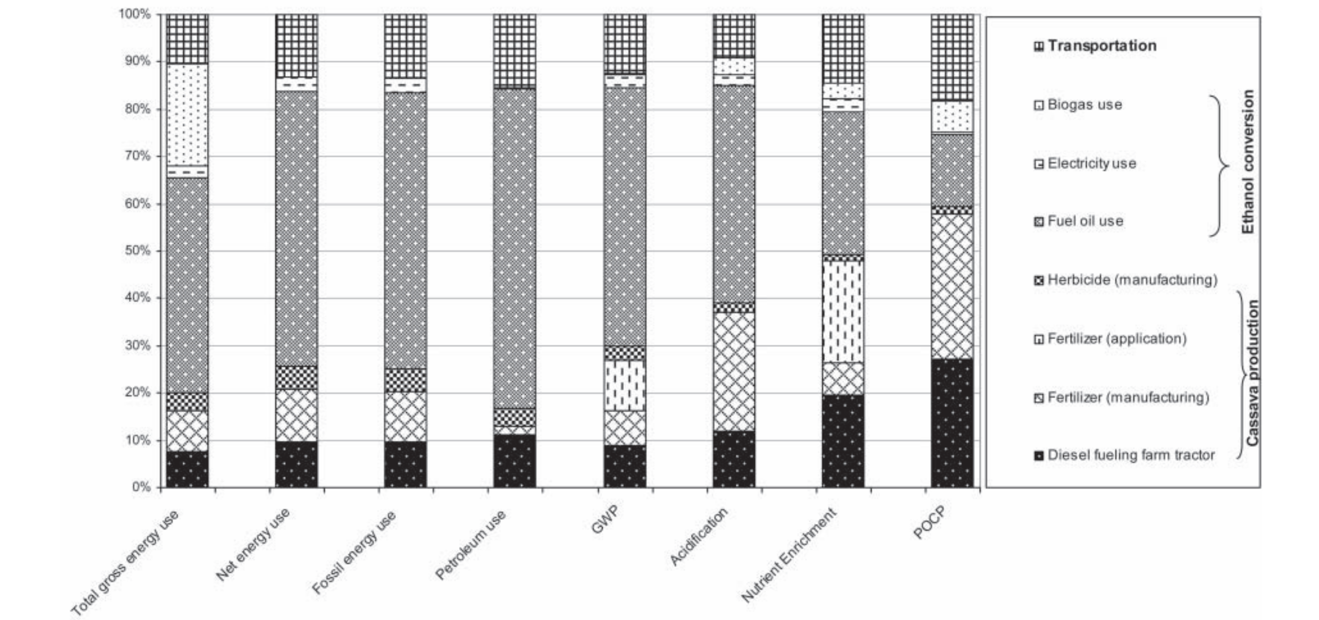

Fig. 4: Characterization results – Contributions to the environmental impacts from ethanol production cycle

rect and indirect) and from the manufacturing of fertilizers. Transportation contributes a relatively small fraction (less than 20%) of energy use as well as environmental impact potentials of the CE production cycle.

Figs. 5 and **6** present the two sets of life-cycle energy use and environmental performance of E10 fuels (E10-a,b,c) and E85 fuels (E85-a,b,c), in comparison with CG which is set at 100%. As shown in the two figures, substitution of biomass for fuel oil to generate process steam in the ethanol conversion process tends to reduce energy and environmental impacts of both E10 and E85. The magnitude of the reductions is larger for E85 than E10. In other words, the substitution has a greater

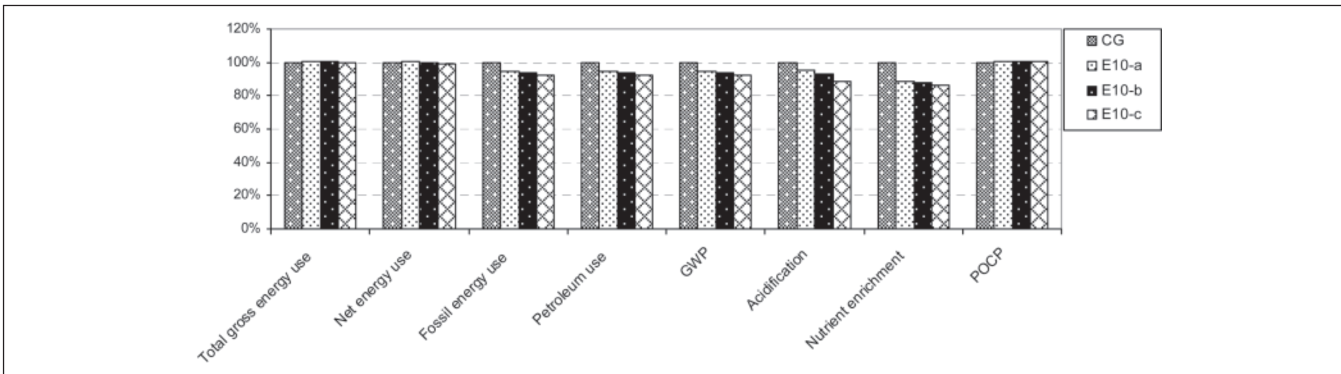

Fig. 5: Comparison of life cycle energy use and environmental performance for E10 fuels and gasoline

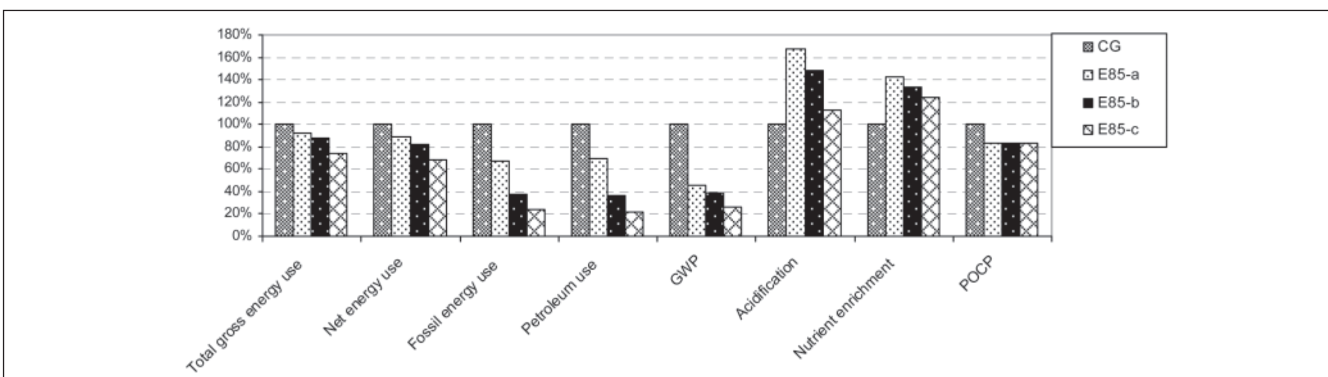

Fig. 6: Comparison of life cycle energy use and environmental performance for E85 fuels and gasoline

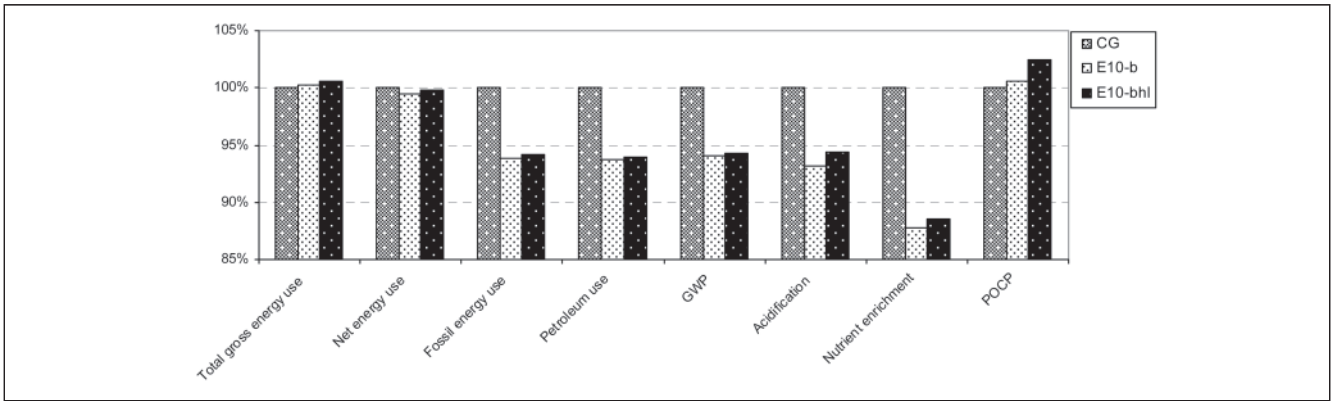

Fig. 7: Effect of inclusion of human labour on the overall energy and environmental performance of E10-b

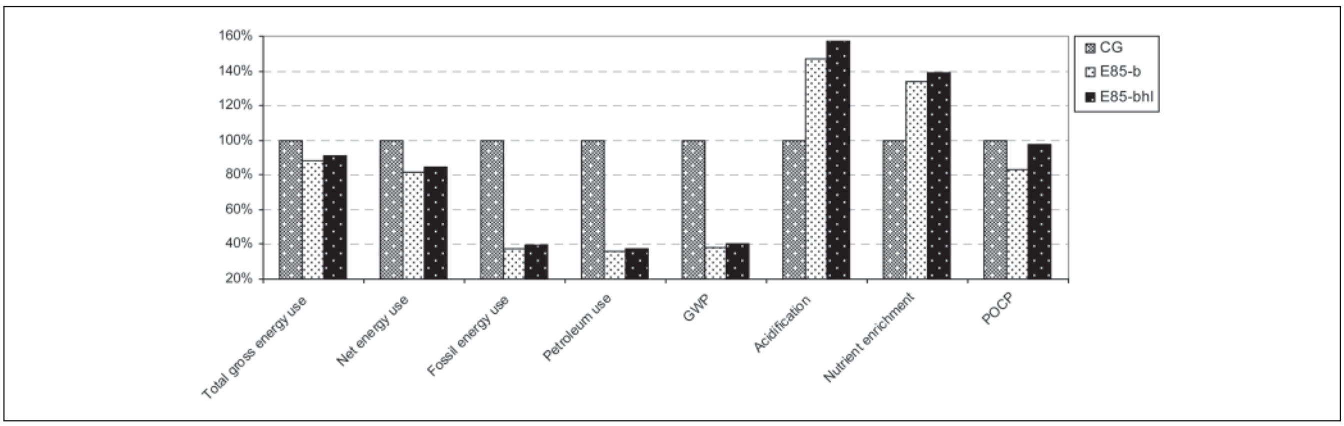

Fig. 8: Effect of inclusion of human labour on the overall energy and environmental performance of E85-b

influence on E85 than on E10, owing to the dominance of ethanol in the fuel mixture, as discussed before. The results can be better interpreted when seen along with Fig. 4.

2.3 Sensitivity analysis for human labour inclusion in the assessment

The results of the sensitivity analysis done for the two ethanol blends with human labour accounting (E10-bhl and E85-bhl) versus the base cases without human labour accounting (E10-b and E85-b) are shown in **Figs.** 7 and 8. For a comparison purpose only, all corresponding results are graphically displayed as percentages relative to gasoline. As seen, an inclusion of human labour input in the assessment increases the environmental loads assigned to the two ethanol blends E10-bhl and E85-bhl, compared to the base cases E10-b and E85-b. The magnitude of the increase in the case of E10 is in the order of 0.2% for petroleum use to 1.8% for POCP. An ethanol content in the blend as high as 85% brings the increase to a range of 1.5% to 14.4%. However, the relative advantages or disadvantages of the blends with respect to CG are not reversed when human labour is included.

3 Conclusions

Based on the results of the study, main conclusions can be drawn as follows:

- Ethanol fuel used in the form of blends in gasoline can help reduce fossil energy use and GHG emissions.
- Using E10 substituting for conventional gasoline also results in less acidification and nutrient enrichment.
- For ethanol production cycle, ethanol conversion is the main source of energy use and most of environmental impacts. It leaves an area for researchers and technicians to work on to maximize ethanol's advantages while minimizing disadvantages. Feedstock cultivation is also a notable contributor to acidification, nutrient enrichment and photochemical ozone creation potentials. A modest rate of energy and energy-carrier inputs in cassava production through appropriate farming practices can help reduce these impacts, i.e. optimising farm inputs.
- Substituting biomass for fossil fuels as the main process energy source in ethanol plants helps improve the fuel's life cycle environmental performance. The substitution has a larger influence on E85 than on E10.
- Human labour, if included in the assessment, increases environmental loads assigned to the two ethanol blends. The increases, however, are not large enough to reverse the sign of the changes (i.e. an increase or decrease) in environmental loads relative to gasoline. For a fair comparison between ethanol production in different countries with different levels of mechanization, human labour input at the farming stage should be included. There is a need, however, to develop a generally acceptable accounting method to quantify labour.

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